Optimization of a Transonic Radial Compressor Stage using CFturbo®, ANSYS-CFX and optiSLang®

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Introduction

CFturbo® - Business Areas

CFturbo® Software & Engineering GmbH

CFturbo® Software
- Turbomachinery Design Software
- Automated Workflows

Engineering
- Turbomachinery Conceptual Design
- CFD/FEA Simulation
- Optimization

CAD & Prototyping
- 3D-CAD Modeling
- Prototyping
- Testing, Validation
**CFturbo® – Software**

- CFturbo® is a modern, powerful and user-friendly software tool for **Conceptual Turbomachinery Design**
- The software is on the market since 2005
- There are more than 120 clients globally
- **CFturbo® modules to design**
  - Pumps
  - Blowers
  - Compressors
  - Turbines
  - Stators and diffusers
  - Volutes
- **Axial pumps, inducers, fans and turbines are available now in CFturbo10.0**
Conceptual Turbomachinery Design Software - CFturbo®

- **Define operating point**
  - $Q$, $\Delta p$, speed, fluid properties;
  - Inlet conditions

- **Fundamental equations**
  - Bernoulli, Euler equation, Mass-, Momentum-, Energy-conservation, ...

- **Empirical correlations**
  - Ability to independently optimize parameters;
  - User can integrate own data

- **Reference geometry - elements from CFturbo**

- **Existing geometry - elements, imported**

- **New or modified components**

- **CFturbo®**

Introducing CFturbo® software, a powerful tool for conceptual turbomachinery design. It allows for the definition of operating points, utilization of fundamental equations, and empirical correlations to optimize parameters and integrate user data. Reference and existing geometry elements are also incorporated to enhance design capabilities.
Typical development process for Turbomachinery components

1. Design
   - Conceptual Design
     - CFturbo®
   - Meshing
     - ANSA, AutoGrid, ICEM, Pointwise, TurboGrid, ...
2. Simulation & Validation
   - Re-computation/optimization interactively or automated
   - CFD/FEA Simulation
     - ANSYS-CFX, FINE/Turbo, PumpLinx, STAR CCM+, ...
3. Product
   - Experiments
     - Prototyping, Testing, Validation
   - 3D-CAD
     - CATIA, SolidWorks, NX, Creo, SpaceClaim, ...
   - Production

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www.cfturbo.com
Initial Design with CFturbo®

Define Design Point

- Mass Flow Rate: \( m_{\text{flow}} = 0.11 \text{ kg/s} \)
- Total Pressure Ratio: \( \Pi = 4 \)
- Machine Speed: \( n = 90000 \text{ min}^{-1} \)

Empirical correlations are used for initial sizing (main dimensions)
Initial Design with CFturbo®

Export Geometry for Meshing
Write CFT-Batch-File
CFD Simulation – Meshing

**Volute**
- Automatic ICEM-Meshing (CFturbo-Script)
- Tet/Prism Hybrid Mesh
- ~520k elements

**Impeller**
- TurboGrid Meshing
- Stators included as Inlet/Outlet-Domain
- ~3 mio elements
**CFD Simulation – Setup**

**Inlet**
- $p_{tot} = 1$ bar
- $T_{in} = 20^\circ C$

**Outlet**
- $m_{flow} = 0.11$ kg/s

**Results**

- **Total Pressure Ratio:** $\Pi = \frac{p_{tot,IF4}}{p_{tot,RSI1}}$
- **Impeller Power:** $P_i = M \cdot \omega$
- **Stage Efficiency:** $\eta_{Stage} = \frac{h_{tot,isen,IF4} - h_{tot,isen,RSI1}}{h_{tot,IF4} - h_{tot,RSI1}}$

Steady State, Frozen Rotor, Total Energy, Air (Ideal Gas)
CFD Simulation – Results
CFD Simulation – Results

Velocity in Stn Frame
- 5.0e+002
- 4.5e+002
- 4.0e+002
- 3.5e+002
- 3.0e+002
- 2.5e+002
- 2.0e+002
- 1.5e+002
- 1.0e+002
- 0.5e+002
- 0.0e+002

Re-design is necessary to meet design goals

<table>
<thead>
<tr>
<th>Total Pressure Ratio $\Pi$</th>
<th>Power Consumption $P_i$</th>
<th>Stage Efficiency $\eta_{\text{Stage}}$</th>
<th>Impeller Efficiency $\eta_{\text{Imp}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8</td>
<td>24,260</td>
<td>0.61</td>
<td>0.81</td>
</tr>
</tbody>
</table>

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www.cfturbo.com
Optimization

- CFturbo® is fully integrated into optiSLang® for comfortable handling
- optiSLang® is master instance and controls the workflow
- Workflow consists of:

![](diagram.png)

- **CFturbo** Turbomachinery Design
- **ANSYS** TurboGrid, ICEM-CFD Meshing
- **ANSYS CFX** Simulation
Optimization Definition

**Challenge / Task**

➢ Find the **best impeller** for a given and **constant volute**!

**Goal**

Stage Efficiency \( \rightarrow \) Max.

**Constraints**

- Power Consumption \( P_i < 25.5 \text{ kW} \)
- Total Pressure Ratio: \( P > 4.0 \)
- Constant Volute

**Parameters**

More than 20 design parameters!

- **Main dimensions**
  - Suction diameter
  - Impeller diameter
  - Outlet width

- **Meridional contour**
  - Axial extension
  - Contour of Hub and Shroud

- **Blade properties**
  - Number of blades
  - Blade angles \( \beta_{B2} \)
  - Blade mean line of main and splitter blade
  - Leading edge of main and splitter blade
  - Relative position of splitter blade
  - Wrap angle for main and splitter blade
Evolutionary Algorithm (EA)

Imitates Evolution ("Optimization") in Nature:

• Survival of the fittest
• Evolution due to mutation, recombination and selection
• Developed for optimization problems where no gradient information is available, like binary or discrete search spaces
• Evolutionary strategy (Rechenberg 1964)
• Genetic algorithm (Holland 1962)
Evolutionary Algorithm (EA)

Terms
- **Individual:** design related to the design parameters
- **Fitness:** objective function, including penalties for constraints
- **Population:** group of individuals in one generation
- **Archive:** set of saved best individuals

Main operators
- **Selection**
- **Recombination (Crossover)**
- **Mutation**
- **Replacement**
Optimisation Cluster elements

Head node = 1x PRIMERGY RX350 S8

- CPU: E5-2637 v2 @ 3.50GHz (4 core)
- MEM: 8*16384 MB /DDR3 /1866 Mhz
- 1*NVIDIA Tesla K40m
- Mellanox FDR 1 port
- 4 * SAS 900GB 10 k
  - 2 disc in RAID1 for RedHat and HCS
  - 2 disc in RAID0 for data

Compute nodes = 8x PRIMERGY CX250 S2

- CPU: 2*E5-2697V2 (12 core, 2.7GHz)
- MEM: 16*8GB /1866 Mhz (on cn1 and cn2 8*16GB)
- Mellanox FDR 1 port
- RAID controller 0/1
- 2 * SAS 900GB 10 k
  - 2 disc in RAID0 for RedHat & data

System stack = Fujitsu HPC Cluster Suite (HCS)

- Windows
- OS: RedHat Enterprise Linux 6.4
- HCS version 2.2.04
- Advanced Edition
- PBSpro: 12.2.0.133411
- ICR certified

Fast interconnect = InfiniBand

- Mellanox FDR for MPI and I/O
- GbE for management and control
RDO Cluster Setup for CFTurbo workflow (Windows)

Head node
RX350
8 cores

Compute nodes
CX250
12 cores per job

Pre-packaged as a ready-to-use appliance

MS HPC Pack/MSMPI accessing Compute Nodes 1..8

Shared disk: /RSMtemp
RAID0, InfiniBand

HeadNode: 16 DP parallel

16 cores per job
## Optimized Design

- Design complies with all constraints!
- Stage efficiency increased by 5% compared to reference!
- Appr. 600 Designs in less than 3 days!

<table>
<thead>
<tr>
<th>Initial</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impeller Diameter</td>
<td>105 mm</td>
</tr>
<tr>
<td>Suction Diameter</td>
<td>56 mm</td>
</tr>
<tr>
<td>Outlet Width</td>
<td>3.2 mm</td>
</tr>
<tr>
<td>N Blades</td>
<td>16</td>
</tr>
<tr>
<td>Blade angle</td>
<td>55°</td>
</tr>
<tr>
<td>Wrap angle</td>
<td>57°</td>
</tr>
</tbody>
</table>

<table>
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<td>3.8</td>
<td>24,260</td>
<td>0.61</td>
<td>0.81</td>
</tr>
<tr>
<td>4.0</td>
<td>23,540</td>
<td>0.66</td>
<td>0.82</td>
</tr>
</tbody>
</table>
Optimized Design

Initial

Optimized

Pressure

3.0e+005
2.7e+005
2.4e+005
2.1e+005
1.8e+005
1.5e+005
1.1e+005
8.3e+004
5.2e+004
2.1e+004
-1.0e+004

[Pa]

Pressure

3.0e+005
2.7e+005
2.4e+005
2.1e+005
1.8e+005
1.5e+005
1.1e+005
8.3e+004
5.2e+004
2.1e+004
-1.0e+004

[Pa]
Optimized Design

Initial

Optimized

Total Pressure in Stn Frame

[-latex+005]

4.5e+005

4.0e+005

3.5e+005

3.0e+005

2.5e+005

2.0e+005

1.5e+005

1.0e+005

5.0e+004

0.0e+000

[Pa]

Total Pressure in Stn Frame

[-latex+005]

4.5e+005

4.0e+005

3.5e+005

3.0e+005

2.5e+005

2.0e+005

1.5e+005

1.0e+005

5.0e+004

0.0e+000

[Pa]
Optimized Design

Initial

Optimized

Velocity in Stn Frame

- 5.0e+002
- 4.5e+002
- 4.0e+002
- 3.5e+002
- 3.0e+002
- 2.5e+002
- 2.0e+002
- 1.5e+002
- 1.0e+002
- 5.0e+001
- 0.0e+000

[m s^-1]
Reduced recirculation zone in volute → Better stage performance
Volute suboptimal → Should be re-designed
Existing workflow for single point turbomachinery optimization

- Parallelized optimization of a full stage radial compressor over the weekend
- Volute has to be customized to the impeller

Open issues:
- CFturbo® outside Workbench does not allow RSM usage
- Empirical CFturbo® knowledge not available in optiSLang®

> Empirical CFturbo® knowledge combined with optiSLang® algorithms enables ultra-fast Turbomachinery optimization by reducing necessary number of optimization designs

Define operating point
- Q, Δp, speed, Fluid properties
- Inlet conditions

Fundamental equations
- Euler-equation of Turbomachinery, Continuity equation, Momentum equation, ...

Empirical functions
- Public knowledge, Proprietary Know-How

CFturbo®
Further developments - workflow for multi-purpose optimization

- designs for wide compressor maps
- determine surge and choke
- full stage simulation including stability and rotor-dynamics
- enhanced accuracy by combined steady and transient simulation
- smart performance map predictions
- ...

http://www.turbobygarrett.com/turbobygarrett/compressor_maps
Thank you for your interest

and

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for their support!

Please visit us in the exhibition area.